More than clean air and tranquillity: Residential green is independently associated with decreasing mortality

Vienneau, Danielle ; de Hoogh, Kees ; Faeh, David ; Kaufmann, Marco ; Wunderli, Jean Marc ; Röösli, Martin

DOI: https://doi.org/10.1016/j.envint.2017.08.012

Originally published at:
Vienneau, Danielle; de Hoogh, Kees; Faeh, David; Kaufmann, Marco; Wunderli, Jean Marc; Röösli, Martin (2017). More than clean air and tranquillity: Residential green is independently associated with decreasing mortality. Environment international, 108:176-184.
DOI: https://doi.org/10.1016/j.envint.2017.08.012

More than clean air and tranquillity: residential green is independently associated with decreasing mortality

Danielle Vienneau[a,b*], Kees de Hoogh[a,b], David Faeh[c], Marco Kaufmann[c], Jean Marc Wunderli[d], Martin Röösli[a,b] for the SNC Study Group

[a] Swiss Tropical and Public Health Institute, Basel, Switzerland

[b] University of Basel, Basel, Switzerland

[c] Epidemiology, Biostatistics and Prevention Institute (EBPI), University of Zurich, Zurich, Switzerland

[d] Empa, Laboratory for Acoustics/Noise control, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland

***Corresponding Author:**

Danielle Vienneau (PhD)

Department of Epidemiology and Public Health

Swiss Tropical and Public Health Institute

Socinstrasse 57, CH-4051, Basel, Switzerland

danielle.vienneau@swisstph.ch

tel: +41 (0)61 284 8398

fax: +41 (0)61 284 8105

Email addresses: danielle.vienneau@swisstph.ch; c.dehoogh@swisstph.ch; david.faeh@uzh.ch; marco.kaufmann@uzh.ch; Jean-Marc.Wunderli@empa.ch; martin.roosli@swisstph.ch

ABSTRACT

Green space may improve health by enabling physical activity and recovery from stress or by decreased pollution levels. We investigated the association between residential green (greenness or green space) and mortality in adults using the Swiss National Cohort (SNC) by mutually considering air pollution and transportation noise exposure. To reflect residential green at the address level, two different metrics were derived: normalised difference vegetation index (NDVI) for greenness, and high resolution land use classification data to identify green spaces (LU-green). We used stratified Cox proportional hazard models (stratified by sex) to study the association between exposure and all natural cause mortality, respiratory and cardiovascular disease (CVD), including ischemic heart disease, stroke and hypertension related mortality. Models were adjusted for civil status, job position, education, neighbourhood socio-economic position (SEP), geographic region, area type, altitude, air pollution (PM_{10}), and transportation noise. From the nation-wide SNC, 4.2 million adults were included providing 7.8 years of follow-up and respectively 363,553, 85,314 and 232,322 natural cause, respiratory and CVD deaths. Hazard ratios (and 95%-confidence intervals) for NDVI [and LU-green] per interquartile range within 500m of residence were highly comparable: 0.94 (0.93 - 0.95) [0.94 (0.93 - 0.95)] for natural causes; 0.92 (0.91 - 0.94) [0.92 (0.90 - 0.95)] for respiratory; and 0.95 (0.94 - 0.96) [0.96 (0.95 - 0.98)] for CVD mortality. Protective effects were stronger in younger individuals and in women and, for most outcomes, in urban (vs. rural) and in the highest (vs. lowest) SEP quartile. Estimates remained virtually unchanged after incremental adjustment for air pollution and transportation noise, and mediation by these environmental factors was found to be small. We found consistent evidence that residential green reduced the risk of mortality independently from other environmental exposures. This suggests the protective effect goes beyond the absence of pollution sources. Environmental public health measures should not only aim at reducing

pollutant exposure, but additionally maintain existing and increase residential green in areas where lacking.

Keywords: Greenness; Green space; Exposure; Noise; Air pollution; Mortality

Abbreviations

CVD: cardiovascular disease

DHEA: didehydroepiandrosterone

HR: Hazard ratio

IHD: ischemic heart disease

IQR: interquartile range

LU-green: green spaces identified by land use classification

NDVI: normalised difference vegetation index

NO_2: nitrogen dioxide

PH: proportional hazard

PM_{10}: particulate matter less than 10μm in diameter

SEP: socio-economic position

SNC: Swiss National Cohort

Highlights

- Residential green is greenness or green spaces around the home address
- Exposure was defined in two ways: satellite NDVI vs. detailed land use classification data
- The two exposure metrics yielded highly comparable hazard ratios
- Residential green reduced natural cause, respiratory and cardiovascular deaths
- The protective effect was independent from transportation noise and air pollution

1. INTRODUCTION

Green spaces are covered partly by grass, trees or other vegetation, and include city parks, community gardens, sports fields as well as natural and forested areas in rural environments. These are a valuable commodity to any community, empowering the local citizens with regard to recreation, social interaction, physical activity, relaxation, and wellbeing. Emerging research and experiments on the potential benefits of natural environments have indicated that exposure to green spaces such as parks, forests and river corridors can reduce stress, negative emotions and blood pressure (Bowler *et. al.* 2010; Pretty *et. al.* 2005; Song *et. al.* 2016). Similar findings have been obtained through observational studies (Alcock *et. al.* 2014; Groenewegen *et. al.* 2006).

Proximity is a key factor in whether or not individuals access green spaces. A recent hospital-based study by Wilker *et. al.* (2014) in Boston, USA showed proximity to green space to be associated with higher survival rates after ischemic stroke. In a study by Coombes *et. al.* (2010), respondents who lived closest to formal parks were more likely to achieve physical activity targets and were less likely to be overweight. Studies have also shown that green spaces are associated with longevity (Jonker *et. al.* 2014; Takano *et. al.* 2002). The few available cohort studies investigating mortality in relation to greenness, evaluated from satellite imagery, and green space proximity indicated protective effects (James *et. al.* 2016; Tamosiunas *et. al.* 2014; Villeneuve *et. al.* 2012; Wilker *et. al.* 2014). A recent meta-analysis of eight studies of varying population size, however, found only a small, non-statistically significant reduced risk for cardiovascular disease (CVD) mortality, with an overall risk ratio of 0.993 (95%-confidence interval: 0.985-1.001) per 10% increase in residential green space (Gascon *et. al.* 2016).

The underlying mechanism for the observed association is unclear. Research to date has focussed on four main pathways in which nature may affect health, specifically: air quality, physical activity, social cohesion, and stress reduction (Bell *et. al.* 2014; Bowler *et. al.* 2010; Hartig *et. al.* 2014; Lee and Maheswaran 2011). It is postulated that all of these pathways are important and likely intertwined. In their study on streetscape greenery and self-reported general and mental health, de Vries *et. al.* (2013) found that social cohesion and stress reduction were more important mediators than physical activity. Various studies, summarised in Kuo (2015), reported positive impacts of nature on specific stress parameters linked to chronic diseases including increased didehydroepiandrosterone (DHEA), adiponectin, and natural killer cells, and a reduction in inflammatory cytokines and elevated blood glucose levels.

In addition to physical activity and mental health, mediation by air pollution and noise may be at play. Air pollution is associated with cardiovascular, respiratory and natural cause mortality; likewise transportation noise has been shown to be associated with cardiovascular and natural cause mortality (Beelen *et. al.* 2014; Héritier *et. al.* 2017; Hoek *et. al.* 2013; Recio *et. al.* 2016a; Recio *et. al.* 2016b). These exposures are also typically reduced in green areas due to buffering (i.e. shielding) from vegetation and an absence of traffic sources, which may be particularly relevant in urban settings. Additional large studies are needed to evaluate the effect of residential green in different settings, and to determine whether the lack of these pollutants explains the observed beneficial associations.

Using the Swiss National Cohort (SNC) we thus aimed to investigate the effects of exposure to residential green on mortality in Switzerland, by specific causes of death considering small scale models of urban-related exposures to air pollution and transportation noise. We define residential green as greenness obtained from the satellite-derived normalised difference vegetation index (NDVI), or designated green spaces identified by detailed land use classification mapping (LU-green), in the area surrounding the home address. While NDVI detects total greenness, e.g. including street greenery and private gardens, LU-green offers the potential to examine associations for specific types of green or proximity to formal parks.

2. MATERIALS AND METHODS

Swiss National Cohort

The SNC is a longitudinal research platform linking the census with data on births, mortality and emigration (Bopp *et. al.* 2009; Spoerri *et. al.* 2010). The SNC was approved by the Ethics Committees of the Cantons of Zurich and Bern. Due to compulsory participation, nearly all persons residing in Switzerland at the time of the census are represented, i.e. 98.6% in 2000 (Renaud 2004). For each person, individual (e.g. sex, date of birth), household (e.g. type of household, socioeconomic status) and building (e.g. geographical coordinate) information are available. Persons living in Switzerland aged 30 years and older on 04 December 2000 (date of the census) were included in this analysis.

Mortality records in the SNC are based on coding of death certificates. We considered associations for all natural causes (ICD10 A00–R99), all respiratory disease (J00-J99), all cardiovascular disease (I00–I99; CVD) and specifically ischemic heart disease (I20-I25; IHD), stroke (I60-I64) and hypertension related disease (I10-I15) identified as the definitive primary cause of death, concomitant, consecutive, or initial disease.

Exposure Assessment

Two metrics were used to assess exposure to residential green: 1) normalised difference vegetation index (NDVI); and 2) detailed land use mapping to identify green spaces (LU-green). Modelled at the address-level, exposures were linked to individuals in the SNC on the basis of XY-coordinate of the home address. Exposure was determined in a 150m and 500m buffer to respectively represent the near surrounding as well as the local neighbourhood (i.e. walking distance).

NDVI is an indicator of greenness based on land surface reflectance, calculated on the basis of cloud and snow-free Landsat scenes collected on a 16-day cycle (spatial resolution: 30x30m). NDVI is measured on a scale from -1 to 1, where: <0.1 represents barren areas, sand or snow; 0.2-0.3 represents shrub and grassland; and values >0.3 indicate increasing intensity of green (Weier and Herring 2000). Previous studies on green space and health use satellite data from one day, typically during the season with the most substantial vegetation growth (Agay-Shay *et. al.* 2014; Wilker *et. al.* 2014). To construct a continuous surface for the whole of Switzerland, we mosaicked available summer NDVI scenes using ArcGIS 10.2. Surfaces for 2000 (i.e. baseline) and 2014 were constructed. Year 2014 was selected as the preferred dataset because the final NDVI surface (using Landsat 8 tiles from 08 June to 19 July, 2014; see supplemental material Table S1) was 100% cloud-free. Address-level correlations between 2000 and 2014 were high (r=0.89). Mean NDVI was extracted at the home location for the buffer distances using focal functions in ArcGIS.

ArcGIS was used to develop spatial layers to capture total green areas in Switzerland, including local and national parks and other publically-accessible spaces where recreation is possible (i.e. green spaces). This included agriculture and forested areas which often have walking trails or accessible roads. We used the up-to-date spatially detailed Swiss topographic landscape model (swissTLM^{3D} 1.4; 1-m accuracy; 2009-2015) with land use classification. The swissTLM^{3D} did not include all natural areas as a class, thus we supplemented the data with forest and agricultural areas from the older Vector25. Both datasets were from SwissTopo. Traffic areas (e.g. airfields, car parks), complex land use (e.g. landfills, power plants) and non-green recreational areas or those deemed not accessible free of charge to the general public (e.g. golf courses, swimming pools, zoos) were excluded. The percent green space in each buffer was calculated.

Fine scale air pollution and transportation noise were also assigned to residential addresses using ArcGIS. We used existing noise models for 2001 from the SiRENE (Short and Long Term Effects of Transportation Noise Exposure) project to determine total (i.e. combined) transportation noise from road, rail and aircraft traffic for each individual at their residential façade (Karipidis *et. al.* 2014). We used the maximum Lden (day-evening-night), representing the average noise over a 24h period with a respective 5 dB and 10 dB penalty for evening and night hours. Continuous noise exposure was censored at Lden 35 dB, a level based on model accuracy and the exposure distribution. Only one percent of records were below 35 dB, thus set to 35 dB in our data set. Results in the SiRENE study further showed that associations with CVD mortality in Switzerland increase from low noise levels (Héritier *et. al.* 2017). Existing data for Switzerland were also available for air pollution and altitude. Estimates for NO_2 and PM_{10} were extracted from the Swiss national dispersion models (i.e. pollumap; 200x200m grids) for year 2000 (Meteotest 2015). As these were highly correlated (r=0.81) we only used PM_{10} in the analysis, because PM_{10} is a more distinct marker for a broad range of air pollution sources, rather than specifically traffic-related air pollution. In addition, we included altitude because it represents the absence of pollution and it was further found to be associated with IHD mortality in Switzerland (Faeh *et. al.* 2016). Altitude, in metres, was obtained from the mapped 25x25m digital terrain model for Switzerland (VECTOR25: SwissTopo).

Statistical Analysis

The association between residential green exposure and specific causes of death were investigated by stratified Cox proportional hazard regression, with age as the underlying time scale. Schoenfeld residuals were used to test the proportional hazard (PH) assumption. An interaction term (exposure*age) to simulate a time-varying exposure was introduced along with the sex stratification (by design) to satisfy the PH assumption. Individual survival histories from 04 Dec 2000 to 31 Dec 2008 were observed among subjects having been at least 30 years old at baseline. Right censoring was applied at the age of emigration, age of death from another cause, or the end of follow-up. Hazard ratios (HRs), and 95%-confidence intervals, were expressed per interquartile range (IQR) increase in residential green exposure at age 60. Categorical models were used to evaluate the shape of the exposure-response relationship for NDVI and LU-green, with plots of natural splines (created in R version 3.3.0) used to confirm the linear relationship (Figures S1 and S2).

Five models were developed, with incremental adjustments. The base model (M1) included the baseline hazard stratified by sex (Exposure, exposure*age). In M2, we adjusted for sociodemographic confounders: civil status (single, married, widowed, divorced); job attainment (high, medium, low, other); quartiles of neighbourhood socio-economic position (SEP) (Panczak *et. al.* 2012); and education (compulsory or less, upper secondary, tertiary, unknown). In M3, we further adjusted for spatial confounders: Swiss region (Lake Geneva, Espace Mittelland, Northwest, Zurich, East, Central, and Ticino); degree of urbanisation (urban, intermediate, rural); and altitude (metres). Finally, we looked at the additional adjustment for PM_{10} ($\mu g/m^3$) in M4, and PM_{10} plus total transportation noise (dB) in M5.

Following the product-coefficient approach from VanderWeele (2011), we conducted a *post-hoc* mediation analysis, on the main outcomes, to assess the extent to which the association between residential green and mortality is mediated by air pollution or transportation noise exposure. The hypothesised DAG is shown in Figure S3. For each potential mediator, we fit two models to calculate the ratio of the indirect effect to the total effects: a) a normal linear regression model for the association between the potential mediator and residential green, and b) a Cox model for the association between residential green and the outcome. Both models (i.e. ‘a’ and ‘b’) were based on M5, i.e. mutually adjusted for the other environmental variables.

In line with previous studies, we *a priori* selected the 500m buffer as the main exposure variable, and considered all deaths for the relevant outcomes (i.e. all = definitive primary cause, concomitant disease, consecutive disease or initial disease). In sensitivity analyses, we explored exposures in the 150m buffers and models for definitive primary cause of death only. We used stratified analysis to explore potential effect modification due to sex, Swiss region, type of area and SEP. We further calculated robust confidence intervals to account for spatial clustering at region (n=7) or canton (n=26) using the Stata vce(cluster) option.

Statistical analyses were conducted in Stata version 14.0.

3. RESULTS

The census in 2000 recorded 7.29 million persons in Switzerland. In this study, 35.6% were excluded because they were under 30 years of age at baseline. A total of 1.6% participants were excluded due to missing building coordinates and 3.8% because the building was non-residential (e.g. hospitals, mobile shelters, collective housing). A further 0.1% and 0.04% had missing covariate information, respectively for socio-economic position and air pollution or transportation noise. The population used for analyses included 4,284,680 individuals accounting for 40,805,591 person-years with a mean follow-up of 7.8 years. During the follow-up period, 363,553 deaths occurred from natural causes of which 23.5% and 63.9%

(24.1%, 8.7% and 18.1%) were respectively from all respiratory diseases and all cardiovascular diseases (specifically IHD, stroke and hypertension related deaths).

The characteristics of the study population at baseline are presented in Table 1 for males and females; supplementary Table S2 includes deaths by cause. The majority of adults were married, living in urban communities and had upper secondary level education or higher. Compared to women, the proportion of all respiratory and IHD deaths was higher in males, while the proportion of stroke and hypertension related diseases was higher in females.

<<Table 1 hereabouts>>

The NDVI and LU-green exposure maps for Switzerland are presented in Figure 1. Pearson's correlation between the 150m and 500m buffers for each metric were high ($r \geq 0.80$); correlations between metrics were also high ($r=0.62$ for 150m; $r=0.77$ for 500m buffer). Summary statistics for the exposure and environmental variables are given in Table 2, with histograms in Figure S4 and correlations in Table S3.

<<Figure 1 hereabouts>>

<<Table 2 hereabouts>>

We found a protective effect of residential green which was stronger in younger individuals (Figure 2). Regarding accuracy of diagnosis, we found only a slight attenuation in HRs when restricting the cohort to adults between 30 - 80 years old (data not shown). As presented in Figure 3 showing the incremental adjustments for NDVI, the HRs for cardiovascular outcomes were attenuated when we adjusted for sociodemographic confounders reflecting regional differences in CVD in Switzerland (Chammartin *et. al.* 2016). After adjusting for the spatial confounders, the HRs in M3 returned to similar values as M1. We also found that incremental adjustment for air pollution and transportation noise did not substantially change the HRs for NDVI and LU-green compared to the adjusted model M3 (Figure 3 and Figure

S5). The final models (M5) for all outcomes are thus additionally adjusted for these environmental variables.

Mediation by air pollution and transportation noise was of minor relevance for the observed association between green space and mortality (Table S4). We estimated that approximately 8% and 2-6% of the green-prevented deaths may be mediated by transportation noise and air pollution, respectively.

<<Figure 2 hereabouts>>

<<Figure 3 hereabouts>>

Results for the specific causes of death in relation to exposure in a 500m buffer are presented in Table 3. After adjustment, we saw a significant protective effect for most investigated outcomes with NDVI exposure when investigating all deaths (e.g., 0.95 [0.94 - 0.96] per IQR NDVI in 500m for CVD mortality). Results for LU-green were similar (e.g., 0.96 [0.95 - 0.98] per IQR LU-green in 500m for CVD mortality), though in some cases slightly attenuated and not statistically significant for the specific sub-types of CVD (IHD, stroke and hypertension related deaths). HRs for the exposures based only on primary cause of death were often attenuated (e.g., HR for NDVI [and LU-green] per IQR in 500m were: 0.96 (0.95 - 0.97) [0.98 (0.97 - 1.00)] for CVD mortality), further most of the CVD sub-types lost statistical significance regardless of exposure metric. Replacing the 500m exposure buffer with the 150m buffer resulted in a slightly stronger protective effect for NDVI but not for exposure assessed with LU-green (Table S5).

<<Table 3 hereabouts>>

The benefit of residential green was found to be greater in females compared to males, though this was only statistically significantly different for all natural causes (p-interaction=0.001), all respiratory (p-interaction=0.045) and all CVD mortality (p-interaction=0.000) (Figure 1,

Table 4). The protective effect of residential green was also stronger in urban communities compared to intermediate or rural for death from all natural causes (p-trend=0.000), all respiratory (p-trend=0.042), all CVD (p-trend=0.000) and stroke (p-trend=0.018). We further found a trend for greater protection from residential green in the highest compared to lowest SEP quartile for death from all natural causes (p-tend=0.000), all CVD (p-trend=0.0066) and hypertension related diseases (p-trend=0.004). In general, the benefit of residential green was less pronounced in the Swiss regions of Lake Geneva and Ticino compared to other regions, with significant heterogeneity across areas found for all natural causes (p-interaction=0.000) and all CVD mortality (p-interaction=0.004) (Table 4). For natural cause, respiratory, CVD and IHD mortality, the robust confidence intervals accounting for spatial clustering were slightly wider than those for our final models which were adjusted for Swiss region. The confidence intervals for stroke and hypertension mortality they were unchanged (Table S6).

<<Table 4 hereabouts>>

4. DISCUSSION

We found consistent evidence that residential green was associated with reduced risk of natural cause mortality (0.94 [0.93 - 0.95] per IQR NDVI in 500m buffer), respiratory mortality (0.92 [0.91 - 0.94]) and all CVD mortality (0.95 [0.94 - 0.96]) including specific causes of CVD mortality, in a cohort of nearly all adults in Switzerland.

There are few available similar cohort studies (James *et. al.* 2016; Villeneuve *et. al.* 2012). Both of these studies used NDVI as the exposure metric; ours is the first to compare NDVI with high quality land use classification data, finding decidedly similar results for the two metrics. The HRs from our national cohort were further highly comparable to the Ontario study by Villeneuve *et. al.* (2012) which included 575,000 adults and reported HRs for: nonaccidental mortality (0.95 [0.94-0.96] per IQR NDVI in a 500m buffer); CVD (0.94 [0.92-0.96]); and non-malignant respiratory disease (0.91 [0.87-0.95]). The Nurses' Health Study likewise reported a HR of 0.88 (0.82-94) per 0.1 unit NDVI in a 250m buffer for natural cause mortality (James *et. al.* 2016).

Previous studies on residential green and mortality treated air pollution as a confounder, finding the models robust to adjustment (Villeneuve *et. al.* 2012; Wilker *et. al.* 2014). The exception is the most recent study where James *et. al.* (2016) specifically investigated air pollution as a mediator. They found air pollution and physical activity played a small mediating role in the relationship, while depression and social engagement were the more important mediators. Regarding environmental factors, our study comes to the same conclusion. The protective effect of residential green on mortality is largely independent of transportation noise and air pollution (Figure S3 and Table S4). According to our mediation analysis, less than 10% of the protective effects of residential green on all natural cause, respiratory and cardiovascular mortality are mediated by these two pollutants. Although measures of mediation should be considered with caution (Rod and Lange 2017; VanderWeele 2011), including these variables in our models may be an over-adjustment and should be considered when interpreting our results.

In line with Villeneuve *et. al.* (2012), we also found that the protective effect of residential green was stronger in younger individuals. Young active people may profit from green space by enhanced physical activity, which is known to improve health (Fuzeki *et. al.* 2017; Reiner *et. al.* 2013). We cannot exclude that inaccuracy in attribution of cause of death in older individuals contributed to this pattern, however our sensitivity analysis restricting the population to adults aged 30-80 did not change the HRs compared to our main models.

We also found the protective effect to be greater in females compared to males. This is in contrast to the ecological study by Richardson and Mitchell (2010) reporting a protective effect of green space on CVD and respiratory mortality for men but not women. Whether this is related to physical activity remains to be seen, and cannot be determined with our data. The Swiss Health Survey indicates that rates of physical activity in men are slightly higher than women (FSO 2013), though it does not distinguish between preference for indoor versus outdoor physical activity which may differ by sex. Our observations, however, might be explained by mothers with young children simply spending more time in and around the home and local parks. A study in Kaunas, Lithuania found green space to be more important to women's health, noting that women frequented green spaces more often than men, likely because of childcare and part-time employment (Tamosiunas *et. al.* 2014). An alternative explanation for the gender effects may be occupational exposures, which is expected to be more relevant for men and thus masking the beneficial effects of residential green, in particular in older men.

We specifically focussed on exposure to residential green rather than access or proximity to parks because we did not have behavioural information on physical activity. While surrounding greenness as obtained from NDVI is more suited for assessing the psychological wellbeing and the modifying effects of pollution, physical activity is best evaluated using surveys and/or measures of access and proximity to green spaces via transport networks or other constructs such as a walkability index. For a detailed review, see Brownson *et. al.* (2009). Coombes *et. al.* (2010), for example, found that frequency of use of formal green space for physical activity declined with distance. This can be particularly important in urban areas where access to countryside is difficult. This is unlikely to be a barrier for our study population, where on average more Swiss engage in physical activity than their European neighbours (72% vs. 32% average for Europe) (FSO 2013; WHO 2006). As well, Swiss cities are comparably small and typically surrounded by agricultural and forested areas accessible and used by the public for recreation thus complicating the assessment of access to green space in a nation-wide study such as ours.

Nieuwenhuijsen *et. al.* (2017) extended the conceptual framework of green space, mechanisms and health effects by Hartig *et. al.* (2014) to include the biodiversity hypothesis which suggests contact with nature is beneficial for the human microbiota and immunomodulatory capacity. As explained in Rook (2013), chronic inflammatory disorders (which can lead to increased risk of CVD) are more common in urban areas where the diversity of microbiota is decreased. This may explain why we found a statistically significant stronger protective effect for urban compared to rural areas i.e. the benefit of green in urban areas may be more pronounced because any increase in microbiota from the additional greenery is beneficial.

The SNC did not include information on the participants' smoking status and other lifestyle variables precluding the control for important confounders. In Switzerland, both smoking and body mass index are strongly associated with SEP for which we adjusted (Faeh *et. al.* 2011; Lohse *et. al.* 2016). Compared to Villeneuve *et. al.* (2012), where such control was possible, our exposure assessment was more precise as we used residential geocodes rather than postcodes.

We further recognise that use of NDVI for year 2014 was not ideal given that our baseline was in 2000, and that we do not evaluate change in exposure over the course of the follow-up. It can be challenging obtaining cloud-free satellite imagery for small study areas, let alone across larger spatial domains with complex topography and rapidly changing climatic conditions such as Switzerland (Fontana *et. al.* 2013). Furthermore, it is not possible to identify clouds based on the NDVI scale. In constructing the NDVI mosaic we thus prioritised cloud-free scenes in order to minimise exposure misclassification. Correlations between

NDVI in 2000 and 2014 were high, as were correlations with LU-green giving confidence in the 2014 NDVI data. The high agreement between the two independent exposure metrics further suggests that NDVI can be a good proxy in study areas where spatially resolved land use classification mapping, such as our LU-green, is not available. Rhew *et. al.* (2011) drew a similar conclusion in their validation study comparing NDVI with psychologist ratings of greenness. A study by Mitchell *et. al.* (2011) comparing metrics based on different resolution land use data sets, though not NDVI, also indicated robust associations. Despite the high correlations, however, there will be spatial differences in the local distribution of exposure depending on the selected metric (see Figure 1 map insets). In our data, this is most noticeable within cities where greenery in neighbourhoods is detected by NDVI, but only parks and other delineated green areas are identified with the LU-green metric. These variations are reflected in the slight differences in our reported HRs, in particular for stroke and hypertension related mortality.

While there are many benefits of residential green, drawbacks can include potential increased asthma and allergy in vulnerable subgroups (Carlsten and Rider 2017) and for environmental injustice through gentrification i.e. increased housing costs and property values in neighbourhoods undergoing greening initiatives (Wolch *et. al.* 2014). Some studies have shown that the beneficial effects are more apparent in persons with low SEP (Dadvand *et. al.* 2012; Maas *et. al.* 2006) and that income related health inequalities were smaller in areas with more green spaces (Mitchell and Popham 2008). Alternatively James *et. al.* (2016) reported no difference in the association between greenness and mortality by SEP. In our cohort we found that the protective effect of residential green was stronger in those that were well off compared to those with low SEP. This does not appear to be related to differences in the quantity of residential green by SEP as the mean NDVI exposure across quartiles of SEP in our cohort was highly consistent (means=0.584-0.590). One may speculate that quality or accessibility of green may be lower in areas of deprivation, for example limited to green traffic islands or corridors which are not accessible. Also other factors such as differential access to health care, stronger social ties and cohesion may be important (de Vries *et. al.* 2013).

5. CONCLUSIONS

This is the first rigorous assessment of the potential benefits of residential green in a virtually complete large population sample with high quality exposure variables, adding to the evidence base that exposure to green in our living environment is beneficial for health. The effect of residential green was independent from other environmental variables. The exposure-response associations we derived for residential green and mortality can be used in subsequent health risk assessments in Europe. Reducing pollution (particularly in deprived areas) may not be enough, and should not replace efforts for maintaining and/or increasing green spaces and access to the public.

DECLARATIONS:

Ethics approval and consent to participate:

The SNC was approved by the Ethics Committees of the Cantons of Zurich and Bern.

Competing interests:

The authors declare that they have no competing interests.

Authors' contributions:

DV, MR study concept; DV, MR study design; JW noise model; KdH, DV exposure modelling and assessment; MK statistical advice; DV statistical and data analysis; DV, MR, DF, MK data interpretation; DV write and revise manuscript; all review and comment on manuscript.

Funding:

This work was supported by the Swiss National Science Foundation (grant nos. 3347CO-108806, 33CS30_134273, 33CS30_148415, CRSII3_147635 and 324730_173330).

Acknowledgements:

We thank the Swiss Federal Statistical Office for providing mortality and census data and for the support which made the Swiss National Cohort and this study possible. We also acknowledge the members of the Swiss National Cohort Study Group: Matthias Egger (Chairman of the Executive Board), Adrian Spoerri and Marcel Zwahlen (all Bern), Milo Puhan (Chairman of the Scientific Board), Matthias Bopp (both Zurich), Nino Künzli (Basel), Fred Paccaud (Lausanne) and Michel Oris (Geneva).

REFERENCES

Agay-Shay, K.; Peled, A.; Crespo, A.V.; Peretz, C.; Amitai, Y.; Linn, S., et al. Green spaces and adverse pregnancy outcomes. Occup Environ Med. 71:562-569; 2014

Alcock, I.; White, M.P.; Wheeler, B.W.; Fleming, L.E.; Depledge, M.H. Longitudinal effects on mental health of moving to greener and less green urban areas. Environ Sci Technol. 48:1247-1255; 2014

Beelen, R.; Raaschou-Nielsen, O.; Stafoggia, M.; Andersen, Z.J.; Weinmayr, G.; Hoffmann, B., et al. Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. Lancet. 383:785-795; 2014

Bell, S.L.; Phoenix, C.; Lovell, R.; Wheeler, B.W. Green space, health and wellbeing: making space for individual agency. Health Place. 30:287-292; 2014

Bopp, M.; Spoerri, A.; Zwahlen, M.; Gutzwiller, F.; Paccaud, F.; Braun-Fahrländer, C., et al. Cohort Profile: The Swiss National Cohort—a longitudinal study of 6.8 million people. Int J Epidemiol. 38:379-384; 2009

Bowler, D.E.; Buyung-Ali, L.M.; Knight, T.M.; Pullin, A.S. A systematic review of evidence for the added benefits to health of exposure to natural environments. BMC Public Health. 10:456; 2010

Brownson, R.C.; Hoehner, C.M.; Day, K.; Forsyth, A.; Sallis, J.F. Measuring the built environment for physical activity: state of the science. American journal of preventive medicine. 36:S99-123.e112; 2009

Carlsten, C.; Rider, C.F. Traffic-related air pollution and allergic disease: an update in the context of global urbanization. Curr Opin Allergy Clin Immunol. 17:85-89; 2017

Chammartin, F.; Probst-Hensch, N.; Utzinger, J.; Vounatsou, P. Mortality atlas of the main causes of death in Switzerland, 2008-2012. Swiss Med Wkly. 146:w14280; 2016

Coombes, E.; Jones, A.P.; Hillsdon, M. The relationship of physical activity and overweight to objectively measured green space accessibility and use. Soc Sci Med. 70:816-822; 2010

Dadvand, P.; de Nazelle, A.; Figueras, F.; Basagana, X.; Su, J.; Amoly, E., et al. Green space, health inequality and pregnancy. Environ Int. 40:110-115; 2012
de Vries, S.; van Dillen, S.M.E.; Groenewegen, P.P.; Spreeuwenberg, P. Streetscape greenery and health: Stress, social cohesion and physical activity as mediators. Soc Sci Med. 94:26-33; 2013
Faeh, D.; Braun, J.; Bopp, M. Prevalence of obesity in Switzerland 1992-2007: the impact of education, income and occupational class. Obes Rev. 12:151-166; 2011
Faeh, D.; Moser, A.; Panczak, R.; Bopp, M.; Roosli, M.; Spoerri, A. Independent at heart: persistent association of altitude with ischaemic heart disease mortality after consideration of climate, topography and built environment. J Epidemiol Community Health; 2016
Fontana, F.; Lugrin, D.; Seiz, G.; Meier, M.; Foppa, N. Intercomparison of satellite- and ground-based cloud fraction over Switzerland (2000–2012). Atm Res. 128:1-12; 2013
FSO. Swiss Health Survey 2012 Overview. in: Office F.S., ed. 14 Health. Neuchâtel; 2013
Fuzeki, E.; Engeroff, T.; Banzer, W. Health Benefits of Light-Intensity Physical Activity: A Systematic Review of Accelerometer Data of the National Health and Nutrition Examination Survey (NHANES). Sports Med; 2017
Gascon, M.; Triguero-Mas, M.; Martinez, D.; Dadvand, P.; Rojas-Rueda, D.; Plasencia, A., et al. Residential green spaces and mortality: A systematic review. Environ Int. 86:60-67; 2016
Groenewegen, P.P.; van den Berg, A.E.; de Vries, S.; Verheij, R.A. Vitamin G: effects of green space on health, well-being, and social safety. BMC Public Health. 6:149; 2006
Hartig, T.; Mitchell, R.; de Vries, S.; Frumkin, H. Nature and health. Annu Rev Public Health. 35:207-228; 2014
Héritier, H.; Vienneau, D.; Foraster, M.; Eze, I.C.; Schaffner, E.; Thiesse, L., et al. Transportation noise exposure and cardiovascular mortality: a nationwide cohort study from Switzerland. Eur J Epidemiol. 32 307-315; 2017
Hoek, G.; Krishnan, R.M.; Beelen, R.; Peters, A.; Ostro, B.; Brunekreef, B., et al. Long-term air pollution exposure and cardio- respiratory mortality: A review. Environ Health. 12:43; 2013
James, P.; Hart, J.E.; Banay, R.F.; Laden, F. Exposure to Greenness and Mortality in a Nationwide Prospective Cohort Study of Women. Environ Health Perspect; 2016
Jonker, M.F.; van Lenthe, F.J.; Donkers, B.; Mackenbach, J.P.; Burdorf, A. The effect of urban green on small-area (healthy) life expectancy. J Epidemiol Community Health. 68:999-1002; 2014
Karipidis, I.; Vienneau, D.; Habermacher, M.; Köpfli, M.; Brink, M.; Probst-Hensch, N., et al. Reconstruction of historical noise exposure data for environmental epidemiology in Switzerland within the SiRENE project. Noise Mapping:3-14; 2014
Kuo, M. How might contact with nature promote human health? Promising mechanisms and a possible central pathway. Front Psychol. 6:1093; 2015
Lee, A.C.; Maheswaran, R. The health benefits of urban green spaces: a review of the evidence. J Public Health (Oxf). 33:212-222; 2011
Lohse, T.; Rohrmann, S.; Bopp, M.; Faeh, D. Heavy Smoking Is More Strongly Associated with General Unhealthy Lifestyle than Obesity and Underweight. PLoS One. 11:e0148563; 2016
Maas, J.; Verheij, R.A.; Groenewegen, P.P.; de Vries, S.; Spreeuwenberg, P. Green space, urbanity, and health: how strong is the relation? J Epidemiol Community Health. 60:587; 2006
Meteotest. Karten von Jahreswerten der Luftbelastung in der Schweiz, Dokumentation zu Datengrundlagen, Berechnungsverfahren und Resultaten der Karten bis zum Jahr 2014. Auftraggeber: Bundesamt für Umwelt BAFU; 2015
Mitchell, R.; Astell-Burt, T.; Richardson, E.A. A comparison of green space indicators for epidemiological research. J Epidemiol Community Health. 65:853-858; 2011
Mitchell, R.; Popham, F. Effect of exposure to natural environment on health inequalities: an observational population study. Lancet. 372:1655-1660; 2008
Nieuwenhuijsen, M.J.; Khreis, H.; Triguero-Mas, M.; Gascon, M.; Dadvand, P. Fifty Shades of Green: Pathway to Healthy Urban Living. Epidemiol. 28:63-71; 2017
Panczak, R.; Galobardes, B.; Voorpostel, M.; Spoerri, A.; Zwahlen, M.; Egger, M. A Swiss neighbourhood index of socioeconomic position: development and association with mortality. J Epidemiol Community Health; 2012
Pretty, J.; Peacock, J.; Sellens, M.; Griffin, M. The mental and physical health outcomes of green exercise. Int J Environ Health Res. 15:319-337; 2005
Recio, A.; Linares, C.; Banegas, J.R.; Diaz, J. Road traffic noise effects on cardiovascular, respiratory, and metabolic health: An integrative model of biological mechanisms. Environ Res. 146:359-370; 2016a
Recio, A.; Linares, C.; Banegas, J.R.; Diaz, J. The short-term association of road traffic noise with cardiovascular, respiratory, and diabetes-related mortality. Environ Res. 150:383-390; 2016b
Reiner, M.; Niermann, C.; Jekauc, D.; Woll, A. Long-term health benefits of physical activity--a systematic review of longitudinal studies. BMC Public Health. 13:813; 2013
Renaud, A. Coverage Estimation for the Swiss Population Census 2000: Estimation Methodology and Results.

Swiss Statistics Methodology Report. Neuchâtel: Swiss Federal Statistical Office; 2004
Rhew, I.C.; Vander Stoep, A.; Kearney, A.; Smith, N.L.; Dunbar, M.D. Validation of the Normalized Difference Vegetation Index as a Measure of Neighborhood Greenness. Ann Epidemiol. 21:946-952; 2011
Richardson, E.A.; Mitchell, R. Gender differences in relationships between urban green space and health in the United Kingdom. Soc Sci Med. 71:568-575; 2010
Rod, N.H.; Lange, T. "Current limits for understanding the underlying causal structures in observational epidemiology: reflections on refined mediation models and crude data". Epidemiol; 2017
Rook, G.A. Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health. Proc Natl Acad Sci U S A. 110:18360-18367; 2013
Song, C.; Ikei, H.; Miyazaki, Y. Physiological Effects of Nature Therapy: A Review of the Research in Japan. Int J Environ Res Public Health. 13; 2016
Spoerri, A.; Zwahlen, M.; Egger, M.; Bopp, M. The Swiss National Cohort: a unique database for national and international researchers. Int J Public Health. 55:239-242; 2010
Takano, T.; Nakamura, K.; Watanabe, M. Urban residential environments and senior citizens' longevity in megacity areas: the importance of walkable green spaces. J Epidemiol Community Health. 56:913-918; 2002
Tamosiunas, A.; Grazuleviciene, R.; Luksiene, D.; Dedele, A.; Reklaitiene, R.; Baceviciene, M., et al. Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. Environ Health. 13:20; 2014
VanderWeele, T.J. Causal mediation analysis with survival data. Epidemiol. 22:582-585; 2011
Villeneuve, P.J.; Jerrett, M.; Su, J.G.; Burnett, R.T.; Chen, H.; Wheeler, A.J., et al. A cohort study relating urban green space with mortality in Ontario, Canada. Environ Res. 115:51-58; 2012
Weier, J.; Herring, D. Measuring Vegetation (NDVI & EVI), http://earthobservatory.nasa.gov/Features/MeasuringVegetation/, accessed 11/22/2014. 2000
WHO. Physical Activity and Health in Europe: Evidence for Action. Copenhagen: World Health Organization; 2006
Wilker, E.H.; Wu, C.D.; McNeely, E.; Mostofsky, E.; Spengler, J.; Wellenius, G.A., et al. Green space and mortality following ischemic stroke. Environ Res. 133:42-48; 2014
Wolch, J.R.; Byrne, J.; Newell, J.P. Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. Land Urban Planning. 125:234-244; 2014

Table 1. Population characteristics at baseline

Characteristic	Male	Female
N (% total)	2,054,083 (47.9)	2,230,597 (52.1)
Age		
Mean (SD)	51.5 (14.6)	53.5 (15.8)
Range	30 - 106	30 - 106
Civil status %		
Single	15.8	12.3
Married	74.1	65.1
Widowed	2.9	12.9
Divorced	7.2	9.6
Mother tongue %		
German	64.4	64.8
French	19.3	19.9
Italian	7.9	6.8
Other	8.4	8.5
Education % [a]		
Compulsory education or less	16.4	30.9
Upper secondary level education	49.9	53.0
Tertiary level education	31.4	13.7
Not known	2.3	2.3
Geographic region %		
Lake Geneva	17.6	18.2
Espace Mittelland	23.0	23.1
Northwestern Switzerland	14.2	14.1
Zurich	17.7	17.6
Eastern Switzerland	13.9	13.6
Central Switzerland	9.1	8.7
Ticino	4.5	4.7
Job Position %		
High	13.3	3.9
Medium	39.4	26.3
Low	20.7	20.3
Other	26.6	49.6
Type of area %		
Urban	63.2	64.8
Intermediate	23.3	22.6
Rural	13.5	12.6
Swiss SEP %		
Quartile 1 (0.4 - 56.2 %)	25.4	24.6
Quartile 2 (>56.2 - 63.5 %)	25.0	25.0
Quartile 3 (>63.5 - 70.7 %)	24.8	25.1
Quartile 4 (>70.7 - 100.0 %)	24.8	25.2
NO_2 (µg/m^3)		
Mean (SD)	22.5 (7.9)	22.7 (7.8)
Median	21.8	22.1
Range	0.8 - 63.4	0.8 - 63.4
PM10 (µg/m^3)		

Mean (SD)	20.4 (3.8)	20.5 (3.8)
Median	20.2	20.3
Range	5.9 - 40.7	6.2 - 40.7
Total Traffic Noise (dB)		
Mean (SD)	56.0 (8.1)	56.1 (8.0)
Median	55.7	55.7
Range	35.0 - 92.2	35.0 - 91.0
Altitude (m)		
Mean (SD)	518 (200)	515 (198)
Median	460	459
Range	193 - 2460	193 - 2460

Notes:

a. Highest completed education/training.

Table 2. Descriptive statistics for exposure variables, in 500 and 150m buffers

Exposure [a]	**500m buffer**	**150m buffer**
NDVI exposure (no unit)		
Mean (SD)	0.59 (0.11)	0.56 (0.11)
Median	0.60	0.57
25, 75th centiles	0.53, 0.66	0.50, 0.63
Range	-0.05 - 0.89	0.02 - 0.90
LU-green exposure (%)		
Mean (SD)	34.91 (27.82)	18.46 (25.31)
Median	30.29	6.04
25, 75th centiles	9.55, 55.54	0.00, 29.48
Range	0.00 - 100.00	0.00 - 100.00

Notes:

a. NDVI = normalised difference vegetation index; LU-green = green spaces identified by land use classification.

Table 3: Hazard ratios (with 95%-confidence intervals) for NDVI[a] and LU-green[a] exposure (per IQR) in a 500m buffer and mortality, age 60

Mortality Outcome	Deaths (n) [b]	NDVI 500m (per IQR) [c]		LU-green 500m (per IQR) [c]	
		M1	M5	M1	M5
All deaths					
Natural cause	363,553	0.92 (0.91 - 0.92)	0.94 (0.93 - 0.95)	0.92 (0.91 - 0.93)	0.94 (0.93 - 0.95)
Respiratory	85,314	0.89 (0.87 - 0.90)	0.92 (0.91 - 0.94)	0.90 (0.88 - 0.92)	0.92 (0.90 - 0.95)
CVD	232,322	0.94 (0.93 - 0.95)	0.95 (0.94 - 0.96)	0.97 (0.95 - 0.98)	0.96 (0.95 - 0.98)
IHD	87,668	0.97 (0.95 - 0.98)	0.98 (0.96 - 1.00)	0.98 (0.96 - 1.00)	0.98 (0.96 - 1.01)
Stroke	31,792	0.95 (0.92 - 0.98)	0.95 (0.93 - 0.99)	0.98 (0.95 - 1.02)	0.99 (0.95 - 1.03)
Hypertension related	65,965	0.95 (0.93 - 0.97)	0.96 (0.94 - 0.98)	1.00 (0.97 - 1.03)	0.99 (0.96 - 1.02)
Definitive primary cause					
Natural cause	351,615	0.91 (0.90 - 0.92)	0.94 (0.93 - 0.94)	0.92 (0.91 - 0.92)	0.93 (0.92 - 0.94)
Respiratory	23,243	0.87 (0.85 - 0.90)	0.93 (0.89 - 0.96)	0.90 (0.86 - 0.95)	0.92 (0.87 - 0.96)
CVD	139,070	0.96 (0.95 - 0.98)	0.96 (0.95 - 0.97)	1.00 (0.98 - 1.02)	0.98 (0.97 - 1.00)
IHD	58,505	1.00 (0.98 - 1.02)	1.00 (0.98 - 1.02)	1.02 (0.99 - 1.04)	1.01 (0.98 - 1.04)
Stroke	21,775	0.95 (0.91 - 0.98)	0.95 (0.92 - 0.99)	1.00 (0.95 - 1.05)	1.00 (0.95 - 1.05)
Hypertension related	13,193	1.04 (0.99 - 1.10)	1.00 (0.95 - 1.06)	1.11 (1.04 - 1.19)	1.07 (0.99 - 1.15)

Notes:

a. NDVI = normalised difference vegetation index; LU-green = green spaces identified by land use classification.

b. All deaths included definitive primary cause of death, concomitant, consecutive, or initial disease.

c. M1 = base model with baseline hazard stratified by sex (Exposure, exposure*age); M5 = adjusted model (M1 + civil status, job position, educational attainment, SEP, region, area type, altitude, PM_{10}, total transportation noise). IQR was 0.14 and 45.99 for NDVI 500m and LU-green 500m, respectively.

Table 4: Effect modification - hazard ratios (with 95%-confidence intervals) per IQR of NDVI[a] in a 500m buffer and mortality, age 60 for model M5

Subgroup	Natural cause [b]	Respiratory [b]	CVD [b]	IHD [b]	Stroke [b]	Hypertension related [b]
Sex						
Males	0.95 (0.94 - 0.96)	0.93 (0.91 - 0.96)	0.97 (0.95 - 0.98)	0.98 (0.96 - 1.00)	0.96 (0.92 - 1.00)	0.97 (0.94 - 1.00)
Females	0.93 (0.92 - 0.94)	0.90 (0.88 - 0.93)	0.92 (0.91 - 0.94)	0.97 (0.93 - 1.00)	0.95 (0.91 - 1.00)	0.95 (0.92 - 0.99)
p-value for interaction [c]	*0.0006*	*0.0452*	*0.0001*	*0.4931*	*0.8588*	*0.4569*
Type of area						
Urban	0.93 (0.92 - 0.94)	0.92 (0.90 - 0.94)	0.93 (0.92 - 0.94)	0.95 (0.93 - 0.97)	0.93 (0.89 - 0.96)	0.93 (0.90 - 0.95)
Intermediate	0.98 (0.96 - 1.00)	0.98 (0.94 - 1.03)	0.98 (0.95 - 1.01)	1.00 (0.95 - 1.05)	1.00 (0.92 - 1.09)	0.98 (0.92 - 1.05)
Rural	0.97 (0.94 - 1.00)	0.96 (0.89 - 1.03)	0.99 (0.95 - 1.03)	0.95 (0.88 - 1.02)	1.06 (0.93 - 1.21)	0.96 (0.88 - 1.05)
p-value for trend [d]	*0.0000*	*0.0417*	*0.0003*	*0.4195*	*0.0184*	*0.1570*
Socio-economic Position						
Quartile 1 - low	0.95 (0.94 - 0.96)	0.92 (0.89 - 0.94)	0.95 (0.94 - 0.97)	0.96 (0.93 - 0.99)	0.95 (0.90 - 1.01)	0.99 (0.95 - 1.03)
Quartile 2	0.95 (0.94 - 0.97)	0.95 (0.92 - 0.98)	0.97 (0.95 - 0.99)	1.00 (0.97 - 1.04)	0.97 (0.92 - 1.04)	0.98 (0.94 - 1.02)
Quartile 3	0.94 (0.93 - 0.95)	0.92 (0.89 - 0.95)	0.95 (0.93 - 0.97)	1.00 (0.96 - 1.04)	0.95 (0.89 - 1.02)	0.94 (0.89 - 0.98)
Quartile 4 - high	0.91 (0.90 - 0.93)	0.90 (0.87 - 0.94)	0.91 (0.89 - 0.93)	0.93 (0.89 - 0.97)	0.91 (0.84 - 0.98)	0.90 (0.85 - 0.95)
p-value for trend [d]	*0.0003*	*0.4650*	*0.0057*	*0.5477*	*0.3369*	*0.0036*
Swiss Region						
Lake Geneva	0.97 (0.96 - 0.99)	0.93 (0.90 - 0.97)	0.94 (0.92 - 0.97)	1.00 (0.96 - 1.05)	0.94 (0.88 - 1.01)	0.93 (0.89 - 0.98)
Espace Mittelland	0.92 (0.91 - 0.94)	0.88 (0.85 - 0.92)	0.93 (0.91 - 0.96)	0.95 (0.91 - 0.99)	0.93 (0.86 - 1.00)	0.95 (0.90 - 1.00)
Northwestern CH	0.90 (0.88 - 0.92)	0.89 (0.85 - 0.93)	0.89 (0.87 - 0.92)	0.93 (0.89 - 0.98)	0.87 (0.80 - 0.96)	0.94 (0.88 - 1.00)
Zurich	0.90 (0.89 - 0.92)	0.92 (0.87 - 0.96)	0.91 (0.89 - 0.94)	0.93 (0.89 - 0.98)	0.96 (0.88 - 1.04)	0.92 (0.87 - 0.98)
Eastern CH	0.93 (0.91 - 0.95)	0.90 (0.86 - 0.94)	0.94 (0.91 - 0.96)	0.99 (0.94 - 1.04)	0.97 (0.88 - 1.06)	0.93 (0.87 - 0.99)
Central CH	0.95 (0.92 - 0.98)	0.92 (0.86 - 0.98)	0.93 (0.90 - 0.97)	0.91 (0.86 - 0.97)	1.01 (0.89 - 1.13)	0.96 (0.89 - 1.04)
Ticino	0.99 (0.96 - 1.02)	0.93 (0.87 - 1.01)	1.01 (0.97 - 1.06)	1.01 (0.94 - 1.08)	0.93 (0.82 - 1.05)	1.02 (0.92 - 1.13)
p-value for interaction [c]	*0.0001*	*0.4268*	*0.0040*	*0.1171*	*0.5507*	*0.8767*

Notes:

a. NDVI = normalised difference vegetation index.

b. Reported HRs and 95%-confidence intervals are for the model M5, baseline hazard stratified by sex (Exposure, exposure*age) and adjusted for: civil status, job position, educational attainment, SEP, region, area type, altitude, PM_{10}, total transportation noise. Reported per IQR (i.e. 0.14). Includes definitive primary cause of death, concomitant, consecutive, or initial disease.

c. p-value of the Chi square test used to assess between-strata heterogeneity.

d. p-value of the Chi square for trend using Stata VWLS (variance-weighted least squares).

FIGURE TITLES

Figure 1. Maps of the NDVI (1A) and LU-green (i.e. parks, fields and forests) (1B) exposure across Switzerland

Figure 2. Effect of exposure to NDVI in a 500m buffer (HR per IQR with 95% confidence interval) on natural cause mortality by age and sex for full model (M5)

Notes: A similar pattern was observed for all outcomes.

Figure 3. Incremental adjustment for environmental factors - HRs for mortality outcomes with NDVI in 500m buffer

Notes: Models: **M1** = base model with baseline hazard stratified by sex (Exposure, exposure*age); **M2** = adjusted for sociodemographic confounders (M1 + civil status, job position, educational attainment, SEP); **M3** = adjusted for spatial confounders (M2 + region, area type, altitude); M4 = adjusted for air pollution (M3 + PM_{10}); **M5** = adjusted for noise (M4 + total transportation noise).

Online Supplement:

More than clean air and tranquillity: residential green is independently associated with decreasing mortality

Danielle Vienneau[a,b*], Kees de Hoogh[a,b], David Faeh[c], Marco Kaufmann[c], Jean Marc Wunderli[d], Martin Röösli[a,b] for the SNC Study Group

[a] Swiss Tropical and Public Health Institute, Basel, Switzerland

[b] University of Basel, Basel, Switzerland

[c] Epidemiology, Biostatistics and Prevention Institute (EBPI), University of Zurich, Zurich, Switzerland

[d] Empa, Laboratory for Acoustics/Noise control, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland

Table of Contents

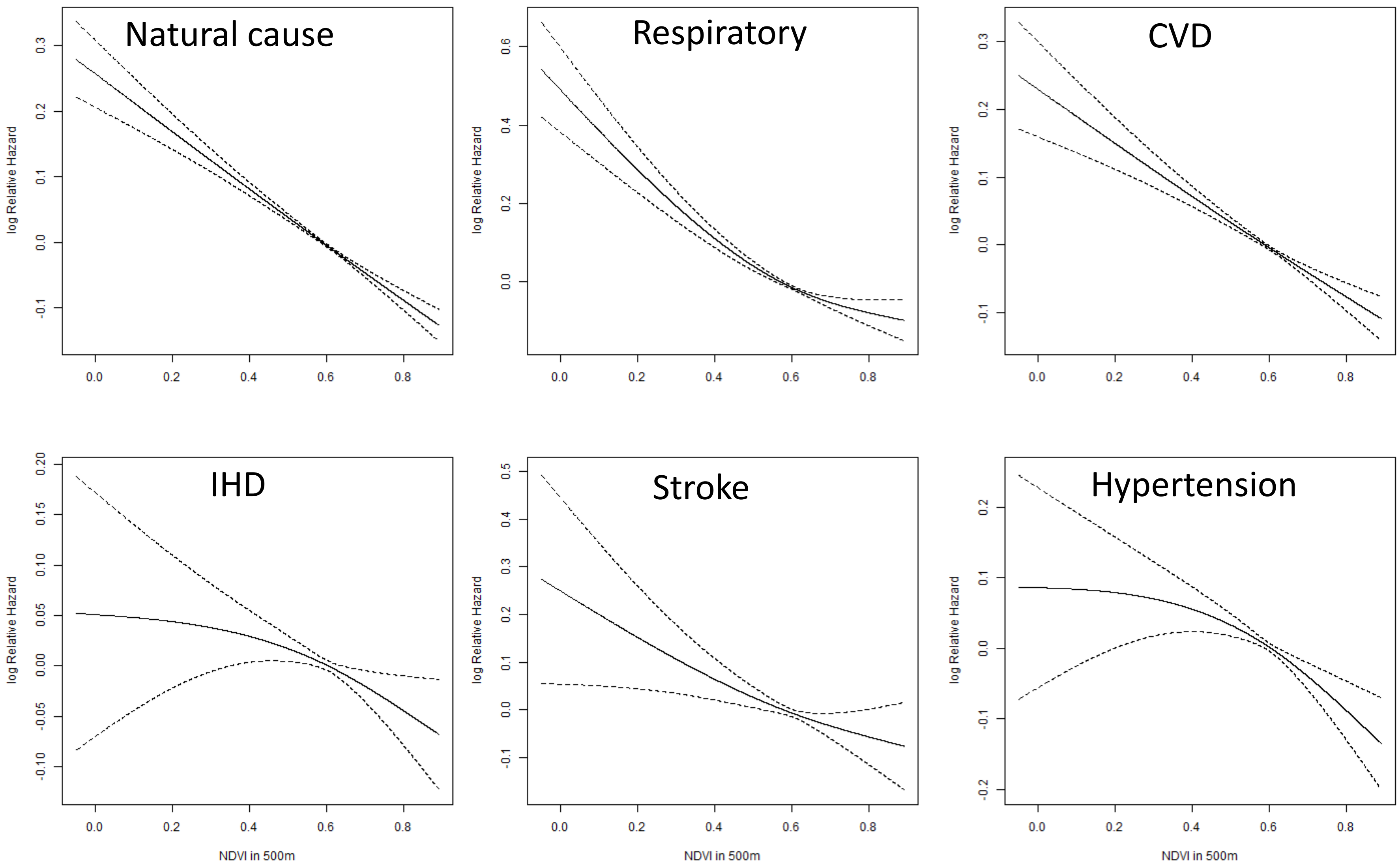


Figure S1. Association between NDVI in 500m and mortality outcomes
Natural splines with 2 degrees of freedom.

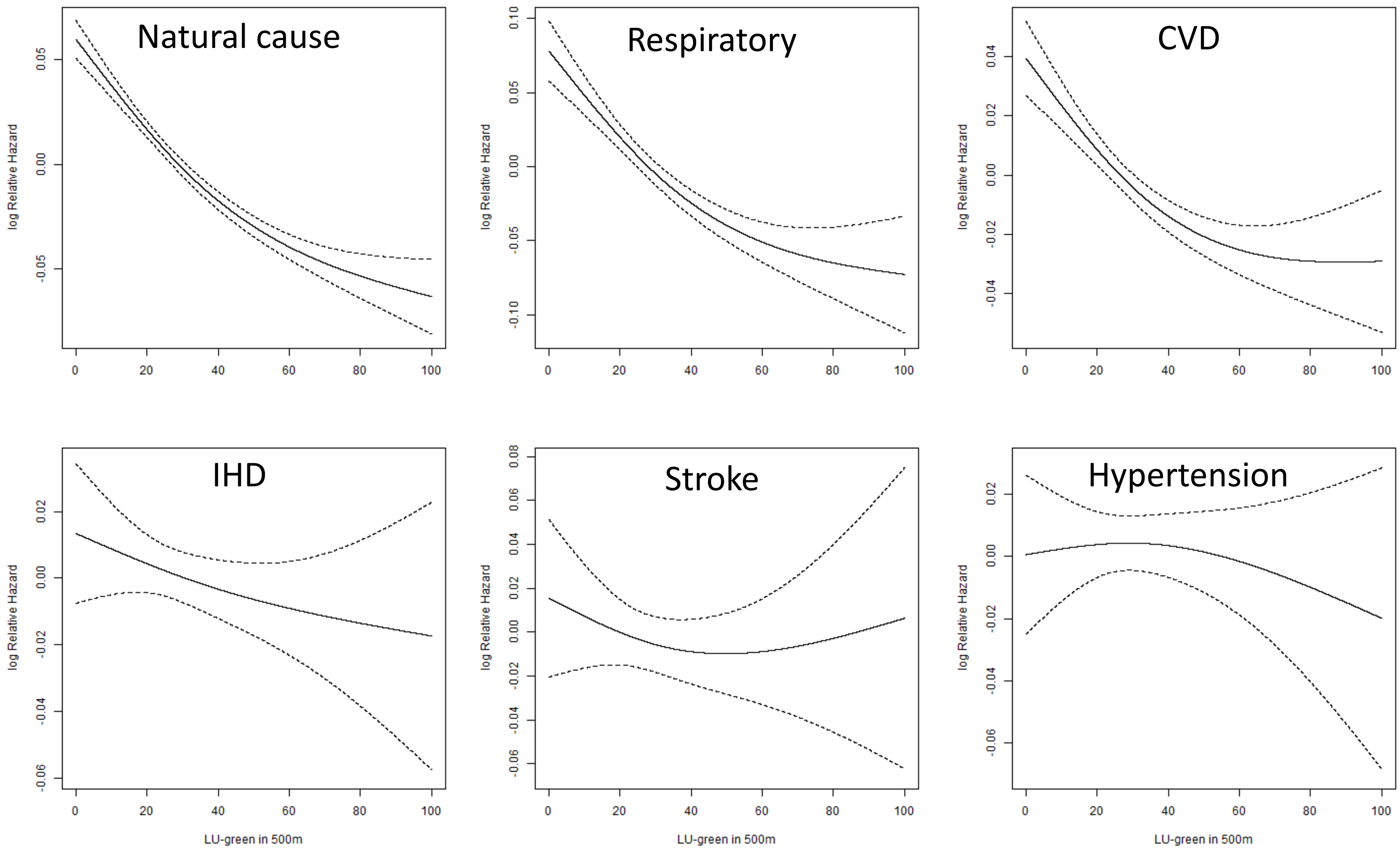


Figure S2. Association between LU-green in 500m and mortality outcomes
Natural splines with 2 degrees of freedom.

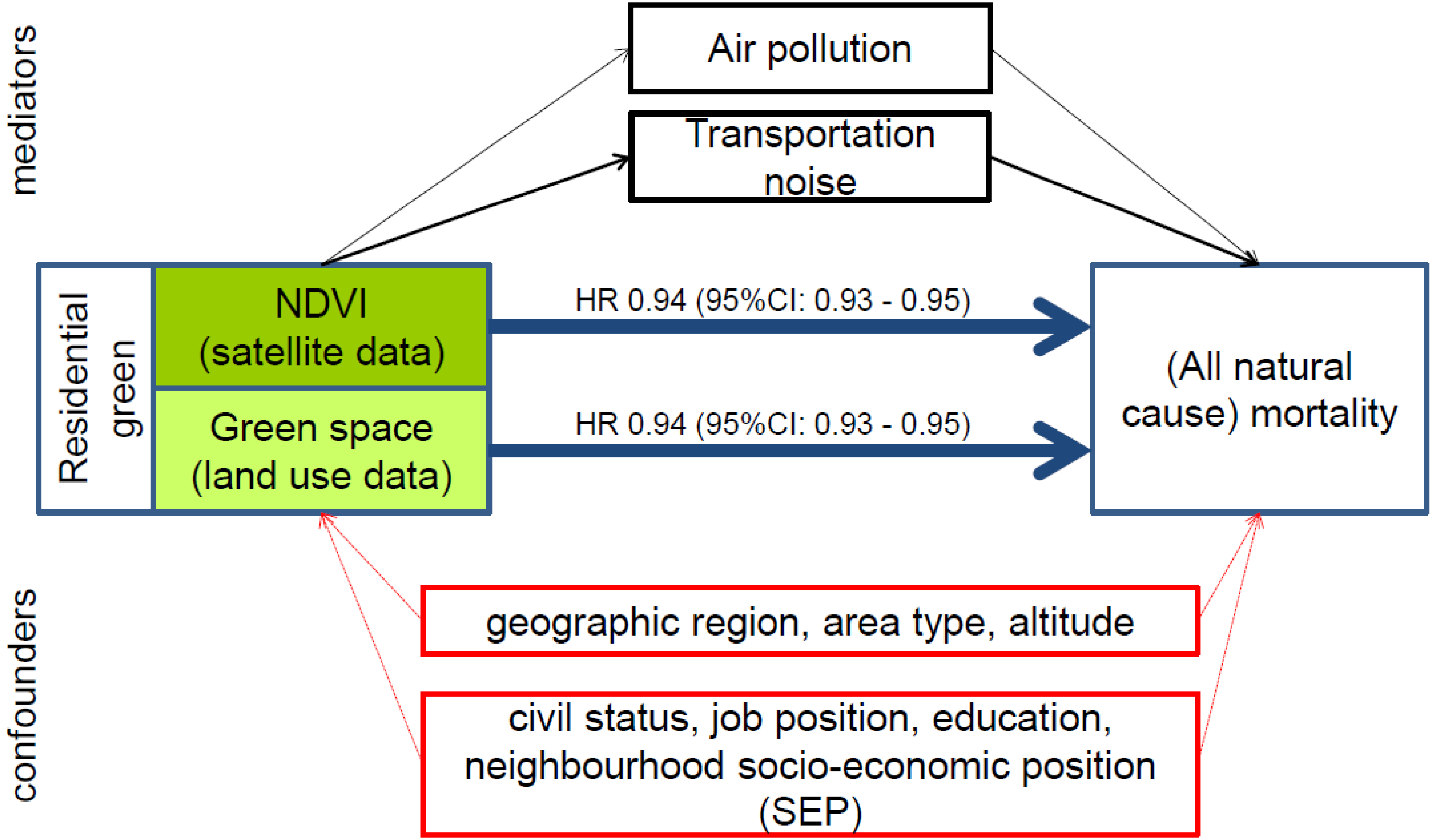


Figure S3. Hypothesised DAG for the association between residential green and mortality
Width of solid lines is proportional to the relevance of the pathway.

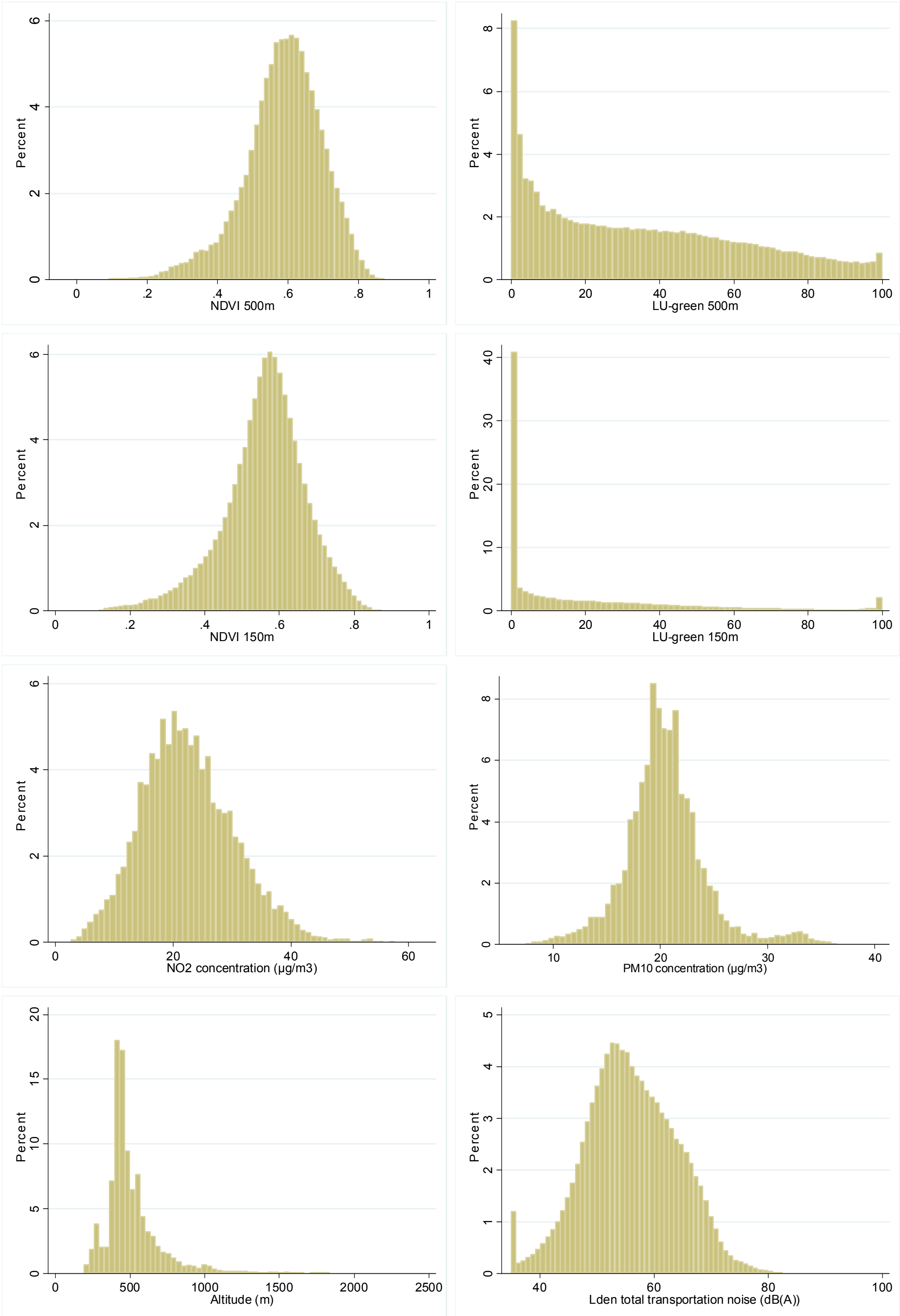


Figure S4. Distributions for the exposure and environmental variables

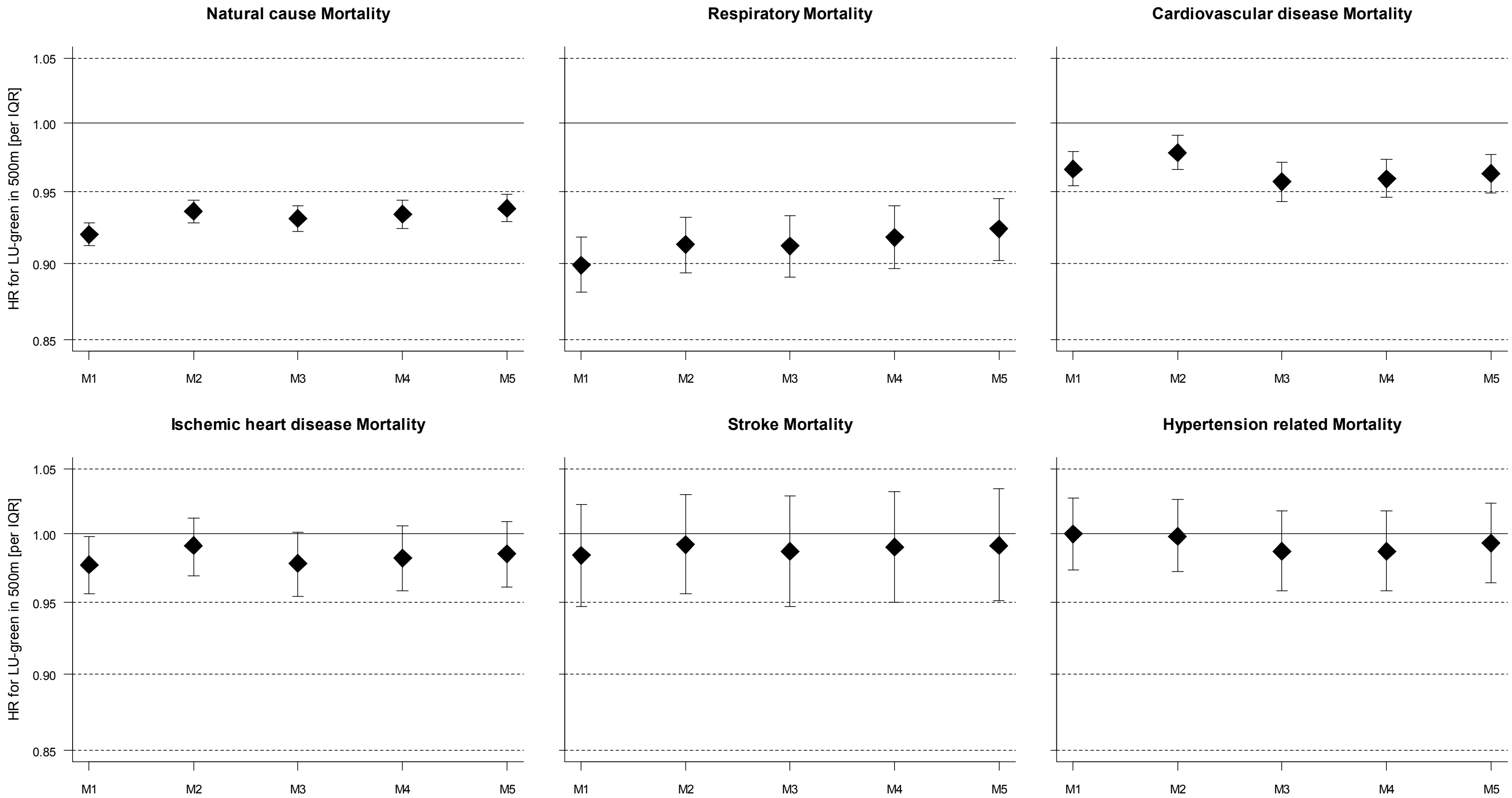


Figure S5. Incremental adjustment for environmental factors - HRs for mortality outcomes with LU-green in 500m buffer
Models: **M1** = base model with baseline hazard stratified by sex (Exposure, exposure*age); **M2** = adjusted for sociodemographic confounders (M1 + civil status, job position, educational attainment, SEP); **M3** = adjusted for spatial confounders (M2 + region, area type, altitude); M4 = adjusted for air pollution (M3 + PM_{10}); **M5** = adjusted for noise (M4 + total transportation noise).

Table S1. Landsat scenes used for the NDVI dataset

Landsat 8			**Landsat 7**		
Scene	**Date**	**Cloud cover (%)**	**Scene**	**Date**	**Cloud cover (%)**
LC81950272014159LGN00 LC81950282014159LGN00	08/06/2014	0 0	LE71940272000154EDC00 LE71940282000154EDC00	02/06/2000	11.68 1.45
LC81930282014161LGN00	10/06/2014	0	LE71960272000168EDC00 LE71960282000168EDC00	16/06/2000	15.18 8.38
LC81940282014184LGN00	03/07/2014	0	LE71930282000179EDC00	27/06/2000	17.99
LC81960272014198LGN00 LC81960282014198LGN00	17/07/2014	0 0	LE71950272000225EDC00 LE71950282000225EDC00	12/08/2000	8.74 18.62
LC81940272014200LGN00	19/07/2014	0			

Table S2. Population characteristics for cohort, including deaths

Characteristic	Cohort	Deaths [a]					
	Full study sample	Natural Causes	Respiratory	CVD	IHD	Stroke	Hypertension-related
N	4,284,680	363,553	85,314	232,322	87,668	31,792	65,965
Age							
Mean (SD)	52.5 (15.2)	74.2 (12.5)	75.7 (11.2)	76.5 (11.1)	76.7 (10.6)	77.4 (10.4)	77.3 (10.0)
Range	30.0 – 106.1	30.0 – 106.1	30.0 – 106.1	30.0 – 105.4	30.1 – 103.6	30.1 – 102.7	30.1 – 103.5
Sex %							
Male	47.9	51.0	57.1	50.2	56.2	44.3	43.1
Female	52.1	49.0	42.9	49.8	43.8	55.7	56.9
Civil status %							
Single	14	9.8	9.0	9.1	7.9	8.8	8.4
Married	69.4	52.5	53.8	50.0	52.5	49.2	47.2
Widowed	8.1	30.5	29.9	34.5	33.3	36.3	38.6
Divorced	8.5	7.3	7.3	6.4	6.2	5.7	5.9
Mother tongue %							
German	64.6	70.2	70.0	73.4	76.0	72.5	73.7
French	19.6	21.0	21.4	19.0	16.0	19.5	19.3
Italian	7.4	6.6	6.6	6.0	6.4	6.0	5.4
Other	8.4	2.2	2.0	1.7	1.6	2.0	1.5
Education % [b]							
Compulsory education or less	24.0	41.3	42.6	43.9	42.4	44.7	47.0
Upper secondary level education	51.5	44.9	44.4	43.5	44.2	42.8	41.8
Tertiary level education	22.2	12.2	11.4	11.0	11.7	10.9	9.5
Not known	2.3	1.6	1.7	1.6	1.6	1.6	1.6
Geographic region %							
Lake Geneva	17.9	17.1	17.4	14.9	12.2	15.9	14.9
Espace Mittelland	23.1	25.1	26.2	25.7	25.4	26.2	25.5

Northwestern Switzerland	14.1	13.9	14.5	14.5	14.9	13.6	14.8
Zurich	17.7	16.9	15.7	17.1	18.2	17.4	17.3
Eastern Switzerland	13.7	14.3	14.2	15.2	15.5	14.7	15.5
Central Switzerland	8.9	8.0	7.6	8.4	9.0	7.9	8.5
Ticino	4.6	4.6	4.4	4.2	4.7	4.3	3.5
Job Position %							
High	8.4	1.4	0.8	1.0	1.0	0.7	0.8
Medium	32.6	6.8	4.6	4.7	4.7	3.6	4.0
Low	20.5	6.6	5.5	5.1	4.9	4.3	4.3
Other	38.5	85.2	89.0	89.2	89.3	91.4	90.9
Type of area %							
Urban	64.0	65.0	64.8	64.0	64.4	64.7	64.0
Intermediate	22.9	21.9	21.6	22.4	22.1	22.3	21.9
Rural	13.0	13.0	13.6	13.6	13.5	13.0	14.0
Swiss SEP %							
Quartile 1 (0.4 - 56.2 %)	25.0	26.7	27.9	26.7	25.8	25.8	26.6
Quartile 2 (>56.2 - 63.5 %)	25.0	27.1	27.4	27.4	27.6	27.2	27.9
Quartile 3 (>63.5 - 70.7 %)	25.0	24.6	24.1	24.9	25.4	25.1	25.1
Quartile 4 (>70.7 - 100.0 %)	25.0	21.6	20.7	21.0	21.2	21.9	20.3

Notes:

a. Includes definitive primary cause of death, concomitant, consecutive, or initial disease.

b. Highest completed education/training.

Table S3. Correlations between the exposure and environmental variables

Pearson's Correlation	**NDVI 500m**	**LU-green 500m**	**NDVI 150m**	**LU-green 150m**	**NO_2**	**PM_{10}**	**Noise**	**Altitude**
NDVI 500m	1							
LU-green 500m	0.77	1						
NDVI 150m	0.83	0.64	1					
LU-green 150m	0.58	0.80	0.62	1				
NO_2	-0.67	-0.70	-0.57	-0.53	1			
PM_{10}	-0.46	-0.50	-0.38	-0.38	0.81	1		
Noise	-0.32	-0.26	-0.35	-0.22	0.35	0.26	1	
Altitude	0.39	0.44	0.28	0.36	-0.58	-0.68	-0.21	1
Spearmans's Correlation								
NDVI 500m	1							
LU-green 500m	0.82	1						
NDVI 150m	0.79	0.65	1					
LU-green 150m	0.66	0.81	0.65	1				
NO_2	-0.67	-0.73	-0.55	-0.58	1			
PM_{10}	-0.53	-0.57	-0.41	-0.44	0.84	1		
Noise	-0.30	-0.25	-0.34	-0.20	0.33	0.27	1	
Altitude	0.47	0.48	0.34	0.38	-0.58	-0.63	-0.21	1

Table S4. Percentage of residential green effect potentially mediated by air pollution and noise

Mortality Outcome	PM_{10}	Transportation Noise
Natural cause	2.4 (-0.2 - 5.5)	8.1 (6.2 - 10.5)
Respiratory	5.6 (1.4 - 11.7)	7.5 (4.6 - 11.8)
CVD	3.1 (-0.6 - 8.5)	7.9 (5.0 - 12.0)

Notes:

Based on NDVI in 500m for age 60, and adjustments used in M5; i.e., age, sex, civil status, job position, educational attainment, and SEP, region, area type, altitude. Models were mutually adjusted for the opposite environmental variable (PM_{10}, total transportation noise).

Table S5. Hazard ratios (with 95%-confidence intervals) for NDVI[a] and LU-green[a] exposure (per IQR) <u>in a 150m</u> buffer and mortality, age 60

Mortality Outcome	Deaths (n) [b]	NDVI 150m (per IQR) [c]		LU-green 150m (per IQR) [c]	
		M1	**M5**	**M1**	**M5**
All deaths					
Natural cause	363,553	0.89 (0.89 - 0.90)	0.93 (0.92 - 0.94)	0.96 (0.95 - 0.96)	0.97 (0.96 - 0.97)
Respiratory	85,314	0.86 (0.85 - 0.87)	0.91 (0.90 - 0.93)	0.95 (0.94 - 0.96)	0.96 (0.95 - 0.98)
CVD	232,322	0.91 (0.90 - 0.92)	0.93 (0.92 - 0.94)	0.98 (0.97 - 0.99)	0.98 (0.97 - 0.99)
IHD	87,668	0.92 (0.91 - 0.94)	0.94 (0.92 - 0.95)	0.98 (0.97 - 1.00)	0.98 (0.97 - 1.00)
Stroke	31,792	0.92 (0.89 - 0.94)	0.93 (0.90 - 0.95)	0.99 (0.96 - 1.02)	0.99 (0.96 - 1.02)
Hypertension-related	65,965	0.91 (0.90 - 0.93)	0.93 (0.91 - 0.95)	1.00 (0.98 - 1.02)	0.99 (0.97 - 1.01)

Notes:

a. NDVI = normalised difference vegetation index; LU-green = green spaces identified by land use classification

b. All deaths included definitive primary cause of death, concomitant, consecutive, or initial disease.

c. M1 = base model with baseline hazard stratified by sex (Exposure, exposure*age); M5 = adjusted model (M1 + civil status, job position, educational attainment, SEP, region, area type, altitude, PM_{10}, total transportation noise). IQR was 0.13 and 29.48 for NDVI 150m and Land use 150m, respectively.

Table S6. Corrected 95% CIs accounting for spatial clustering at region and canton: HR for NDVI[a] in 500m [per IQR], age 60

Mortality Outcome	M5	M5 – robust variance: region[b]	M5 – robust variance: canton[c]
Natural cause	0.94 (0.93 - 0.95)	0.94 (0.92 - 0.97)	0.94 (0.92 - 0.96)
Respiratory	0.92 (0.91 - 0.94)	0.92 (0.89 - 0.96)	0.92 (0.90 - 0.95)
CVD	0.95 (0.94 - 0.96)	0.95 (0.93 - 0.97)	0.95 (0.93 - 0.97)
IHD	0.98 (0.96 - 1.00)	0.98 (0.95 - 1.01)	0.98 (0.95 – 1.00)
Stroke	0.95 (0.93 - 0.99)	0.95 (0.94 - 0.97)	0.95 (0.93 - 0.98)
BP	0.96 (0.94 - 0.98)	0.96 (0.93 - 0.98)	0.96 (0.93 - 0.98)

Notes:
a. Reported HRs and 95%-confidence intervals are for the model M5, baseline hazard stratified by sex (Exposure, exposure*age) and adjusted for: civil status, job position, educational attainment, SEP, region, area type, altitude, PM10, total transportation noise. Reported per IQR (i.e. 0.14).
b. 7 Swiss regions
c. 26 Swiss cantons

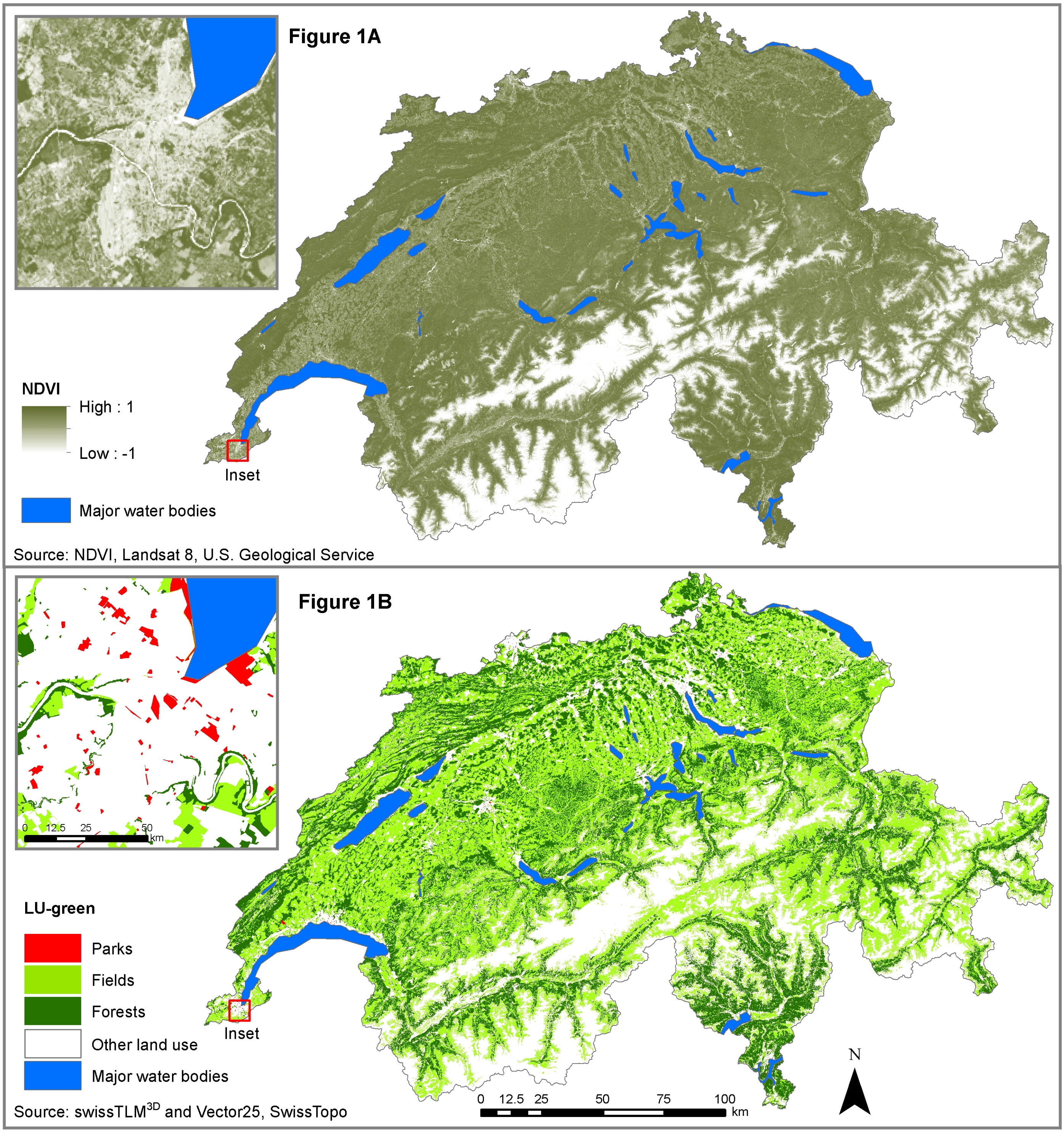
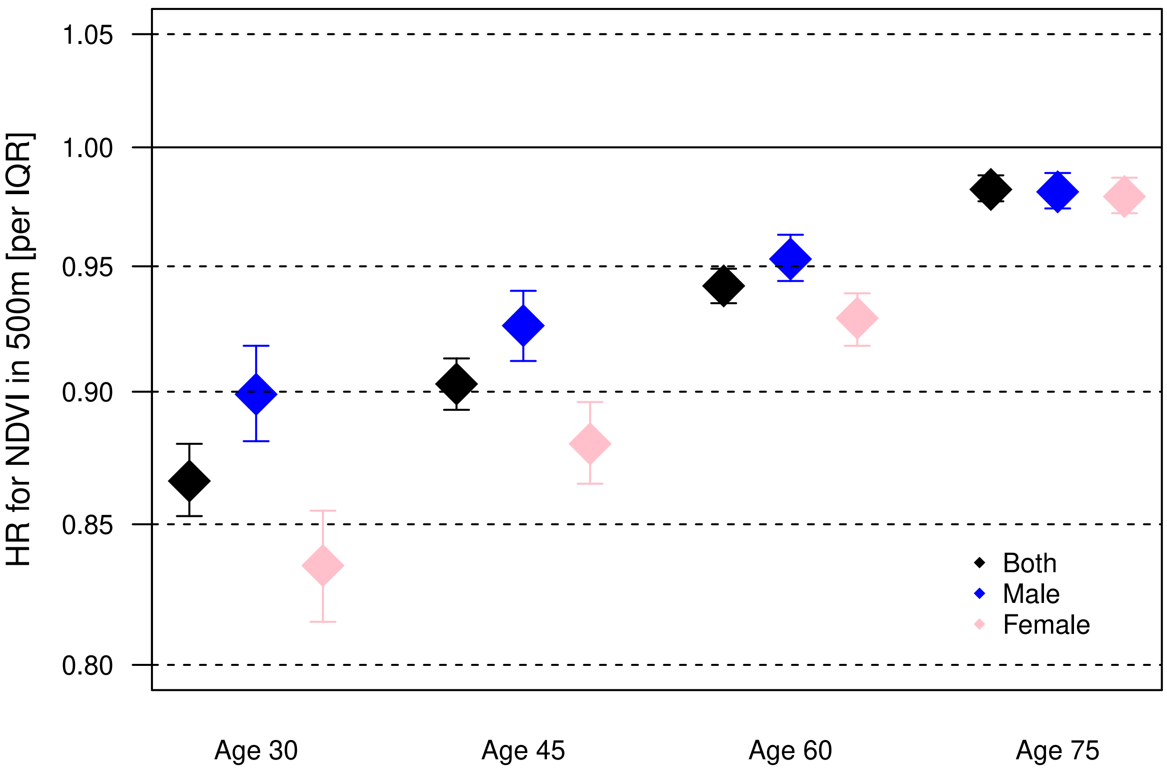
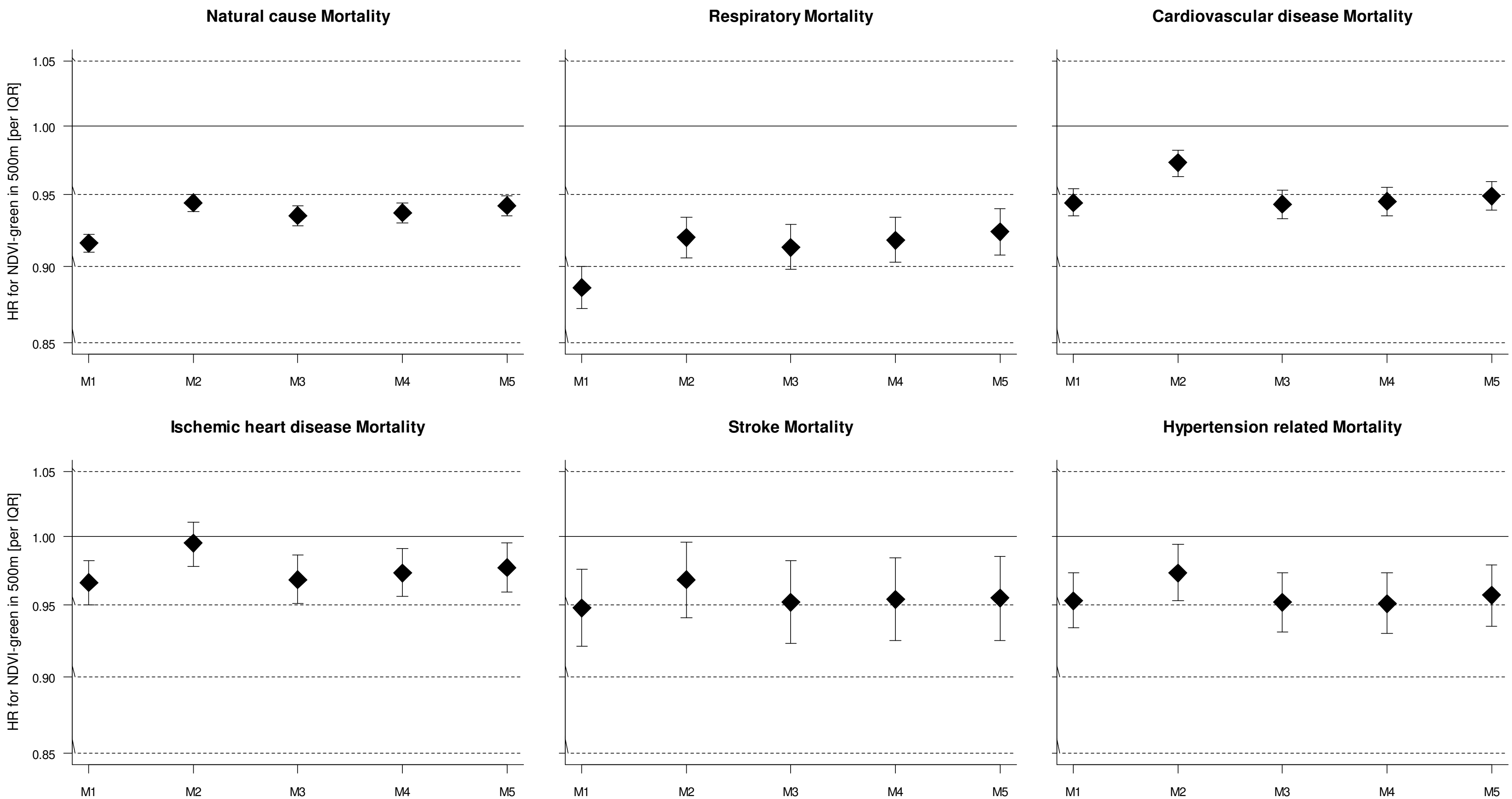


Figure 1A
NDVI
High : 1
Low : -1
Inset
Major water bodies
Source: NDVI, Landsat 8, U.S. Geological Service
Figure 1B
0 12.5 25 50 km
LU-green
Parks
Fields
Forests
Other land use
Major water bodies
Inset
Source: swissTLM3D and Vector25, SwissTopo
0 12.5 25 50 75 100 km
N


HR for NDVI in 500m [per IQR]
1.05
1.00
0.95
0.90
0.85
0.80
Both
Male
Female
Age 30
Age 45
Age 60
Age 75



Natural cause Mortality
Respiratory Mortality
Cardiovascular disease Mortality
Ischemic heart disease Mortality
Stroke Mortality
Hypertension related Mortality
HR for NDVI-green in 500m [per IQR]
1.05
1.00
0.95
0.90
0.85
M1
M2
M3
M4
M5